REAL TIME MEASURES OF EFFECTIVENESS

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LIST OF ACRONYMS

ATMS	Advanced Traffic Management Systems
APTS	Advanced Public Transportation Systems
VMS	Variable Message Signs
HAR	Highway Advisory Radio
ATIS	Advanced Traveler Information System
HOV	High Occupancy Vehicle
TOC	Traffic Operations Center
FHWA	Federal Highway Administration
VDOT	Virginia Department of Transportation
WSDOT	Washington Department of Transportation
ODOT	Ohio Department of Transportation
VDOT	Virginia Department of Transportation
WDOT	Wyoming Department of Transportation
MnDOT	Minnesota Department of Transportation
NYDOT	New York Department of Transportation
Caltrans	California Department of Transportation
PeMS	Performance Measurement System
CCTV	Closed Circuit Television
PTZ	Pan Tilt and Zoom
TTI	Texas Transportation Institute

EXECUTIVE SUMMARY

Growing congestion levels are an increasing problem, hindering efficient movement. An increase in congestion levels also mean increases in vehicular emissions and pollution to the environment. State departments of transportation (DOTs) and local municipalities cannot keep pace with growing traffic. Building our way out of congestion is no longer an option due to escalating construction costs combined with insufficient funds and right-of-way constraints. Intelligent Transportation Systems (ITS), such as Advanced Traffic Management Systems (ATMS), promote more efficient utilization of the available capacity resulting in increased productivity and safety on existing transportation facilities. DOTs across the country are employing Advanced Traveler Information Systems (ATIS) to inform drivers of traffic situations and redirect traffic away from congestion areas. This is the essence of ITS and more efficiently utilizing the available capacity of a network. To support these ITS and ATIS programs, data is needed in real-time to support Real-time measures of effectiveness (MOEs). These MOEs help decision makers inform drivers as to the traffic situation at a given time. Detection devices, including cameras, roadway detectors, and roadside incident reports, are some of the data sources available for helping make decisions.

UDOT continually has endeavored to provide an efficient travel environment to commuters and traffic communities in general. With this objective, it has installed a comprehensive ATMS, which components include: remote traffic controlled signal system, a ramp metering system, Variable Message Signs (VMS), High Occupancy Vehicles Lanes (HOV), Highway Advisory Radio (HAR), complete freeway video coverage, and Traveler Information system. Freeways and arterials provide the data, which is later processed at the Traffic Operations Center (TOC) and then disseminated to the public through Variable Message Signs (VMS) and Highway Advisory Radio (HAR). The TOC also manages arterial traffic signal control throughout the Salt Lake Valley.

Measuring functionality and performance of the ATMS should be monitored continually to determine its effectiveness. The performance measures help UDOT assess the ATMS subsystem's effectiveness in providing trips that have fewer delays and congestion on roads. To quantify the ATMS benefits, various measures of effectiveness (MOEs) can be developed. If these MOEs incorporate real-time measures from automated data collection, then the MOEs can continuously be measured and provide decision making information. Computing the measures of effectiveness involves collecting large amounts of data. When done manually, a data collection becomes cumbersome and introduces manual errors, presenting an inaccurate depiction of ATMS efficiency. The presence of in-pavement data collectors and the Closed Circuit Television (CCTV) cameras along different highways and freeways provide necessary traffic data. This data can be manipulated automatically to generate the required measures of effectiveness. Consequently, the scope of the Utah Traffic Lab's research lies in the development of algorithms, which would automate the different measures of effectiveness for different components of the ATMS.

Providing decision makers with MOEs allows them to make informed decisions about the transportation system operation. Providing this information to commuters allows them to make informed decisions about travel mode and opportunities. If commuters are aware that travel times and travel speeds are much lower during a certain time period, them they can adjust their travel behavior to avoid the more congested periods. Most roads are not congested throughout the day. There is sufficient capacity to accommodate demand if the demand can be spread over a sufficient time interval. If the demand is concentrated in a small time period, then congestion occurs. Even with the recently reconstructed I-15, there is an approximate 20-minute PM peak congested period on the southern portion of the Salt Lake Valley. This is recurring congestion on a typical weekday where demand exceeds capacity. If that demand could be spread over a larger time period, the congestion could be eliminated. ATIS systems are supported by MOEs and inform drivers of delays due to recurring and non-recurring congestion. Non-recurring congestion is difficult to estimate, but informing drivers of recurring congestion allows them to decide whether they want to travel in congestion.

CHAPTER 1. INTRODUCTION

Traffic increases day after day. More automobiles and trucks ply on freeways and arterials than ever before. The main streets and highways of previously suburban communities and towns are fast becoming arterials of increasingly non-radial, urbanized travel as the demand for transportation services increases. It has been estimated that the average weekday vehicle miles of travel is projected to increase from 40.7 million in 1995 to 76.9 million in 2020. The annual growth in Vehicle Miles of Travel (VMT) during the next 25 years is projected to be 2.6 percent higher than the projected annual growth in population. VMT-per capita is projected to increase from 25.1 million in 1995 to 28.5 million in 2020. According to the 2001 Urban Mobility report [7], the average annual delay per person has increased from 11 hours in 1986 to 36 hours in 1999. And one-third of the daily traffic in the 68 urban areas is congested.

With such an increase in auto population, congestion has reached critical proportions and poses a threat to the institution of transportation and its services. An increase in the number of incidents is directly related to high levels of congestion on roads. More than 50 percent of today's incidents are attributed to highly congested traffic conditions. Congestion, which is a major contributor of vehicle emissions, pollutes the environment. Also the cost of congestion rises with each passing year. The total congestion bill for the 68 areas [7] studied under by Texas Transportation Institute (TTI) in 1999 came to $78 billion, which was the value of 4.5 billion hours of delay and 6.8 billion gallons of excess fuel consumed.

The state DOTs and the local municipalities, which are responsible for providing safe, efficient, and reliable travel conditions to the road users, cannot keep pace with the increasing vehicle miles being logged each year. Expanding the highway network to meet the growing demand isn't an option for two reasons: escalating construction costs and the departmental agencies' insufficient funds. Also it is not economically viable to obtain right of way conforming to all local environmental regulations in most metropolitan cities. The emphasis of the DOTs has been to provide a faster and efficient transportation involving low investment and producing high returns. The constant improvements in computer technology have made it easier for traffic detection, monitoring and analysis. Sophisticated and advanced technological systems, like the Intelligent Transportation systems, involve high end communications and software traffic demand and supply management strategies. These systems incorporate telecommunications, video and computer sensing, and high-end electronics that provide real time transportation information. ITS systems provide information to manage transportation, increasing travel efficiency and safety as well as dramatically improving travel options and experiences for the road users.

ITS amalgamates core strategies like the ATMS, Incident Management System, Advanced Traveler Information System (ATIS) to manage and exhibit control over different aspects of surface transportation, such as congestion management and delay reduction. Specifically ITS can be subdivided into ATMS, ATIS, Incident Management, Electronic Toll Collection, Transit Management (APTS), and the Automated Fare Payment System (AFPS). Among these control strategies, ATMS is the most important and critical to traffic management and helps provide efficient mobility to the public.

UDOT aims to provide a safe, congestion free travel environment. Hence, it has installed ATMS on the freeways and major arterials in the Salt Lake City area. The ATMS is constantly supported by traffic data coming into the TOC. The TOC works as a hub of traffic control operations receiving and analyzing real time traffic information obtained through video cameras and automatic traffic detectors placed at appropriate locations on arterials and highways. After assessing traffic condition TOC then disseminates information through variable message signs (VMS), highway advisory radio (HAR) and activates the surface street traffic signal control system.

To justify its use UDOT constantly must be aware of its efficiency since most of the traffic management strategies are linked with the effective functioning of ATMS devices. Awareness comes through establishing performance measures for different ATMS components.

UDOT has been measuring effectiveness of the systems offline through a manual means of data collection and manipulation. This procedure becomes slow and consumes time, when large data sets are involved, hence effectively defeating the purpose of using ATMS, i.e., to provide a comprehensive real time traffic control. A viable alternative is to automate performance measures used for studying the effectiveness of ATMS. UDOT does not have automatic methods to measure them. The current procedure of field evaluations is a cumbersome process, as this involves huge data sets and may provide superficial or erroneous results due to mismanagement in data handling by the operator. Consequently the Utah Traffic Lab (UTL) has researched into ways to develop real time performance measures for ATMS. UTL has developed algorithms, which would automatically compute MOEs for the ATMS devices and report their performance to the TOC.

The goal of this research is to identify and determine methods to automatically compute measures of effectiveness when supplied with real time traffic information. The data is being fed in to the system through loop detectors, system detectors, PTZs and CCTVs that already are in place in the field. To fulfill research requirements, the algorithms must satisfy the following objectives:

- Address the performance effectiveness of the system
- Incorporate quantifiable and acceptable measures of effectiveness
- Compute and report the effectiveness of each of the ATMS components back to TOC

1.1 Research Goals

- Literature review of any real time measures of effectiveness.
- Select measures of effectiveness obtainable from existing traffic infrastructure and determine selection intervals.

- Develop algorithms that would generate the automated measures of effectiveness for the incoming data at the Traffic Operations Center (TOC).

1.2 Major Tasks

- Review existing examples of automated measures of effectiveness for different ATMS across the country.
- Identify those measures of effectiveness that can be obtained from the existing devices.
- Develop algorithms for computing the measures of effectiveness.

CHAPTER 2. MOE PURPOSE AND DEFINITION

2.1 Performance Measurement

The following paragraphs discuss the performance measurement impacts a system has on its environment and people. The performance of any transportation system closely affects the lives of people using the facility or system. This is more pertinent in cases when the system supports transportation operations throughout a city, region or county. The system performance implications are extensive as the transportation of goods and mobility of people are key elements driving a region's economy.

Some of the long term strategies to accommodate increasing demand are to expand the existing system handling capabilities, enhancing facility conditions, regulation of traffic flow through demand management and installation of intelligent systems for more efficient operations. Even though the above are more ideal measures, operations of the system can be greatly improved by increasing traffic surveillance, monitoring and gathering data for obtaining its performance. Often single bottleneck locations cause a majority of the system delay. Hence system performance measurement is a key factor in identifying congestion points and reacting to them appropriately. Performance measuring is critical to the decision-making process and providing high quality transportation service to the end user. Performance measurement also helps in validating costs incurred in installation and set up of the service through a cost-benefit assessment where transportation benefits can be quantified into a monetary value.

2.1.1 Performance Measurement Objectives

The National Performance Review defines performance measurement as*: "A process of assessing progress toward achieving predetermined goals, including information on the efficiency with which resources are transformed into goods and services (outputs), the quality of those outputs (how well they are delivered to clients and the extent to which clients are satisfied) and outcomes (the results of a program activity compared to its intended purpose), and the* *effectiveness of government operations in terms of their specific contributions to program objectives."*

Banks [3] talks of the following performance measurement objectives, which are pertinent to any agency involved in performance measurement:

- Monitor traffic systems and equipment that require replacement
- Quantify the performance effectiveness of the system
- Report the performance to higher authorities and public
- Provide scope for further research in improving the effectiveness of the system

2.1.2 Reasons for Performance Measurement

Pickrell and Neuman summarized major reasons to adopt performance measurements based on the number of performance based planning cases in US as:

(a) Accountability: Performance measurement provides means for determining whether resources are allocated based on priority needs identified by reporting on the performance and results to higher-level entities.

(b) Efficiency: Performance measurement pays attention to the actions and resources on organizational outputs and the process of delivery

(c) Effectiveness: Performance measurement liaisons between the ultimate outcomes of policy decisions, such as providing HOV lane on some corridors and the immediate actions of transportations strategies like making left turns exclusive or allowing curb parking on streets linking downtown shopping centers.

(d) Communications: Performance measurement communicates useful information to the end user, such as the estimated travel time for a route, the average speed on a particular link in a network. It also can provide better information to the public and stakeholders on the progress of the work intended to achieve desired goals and objectives.

(e) Clarity: Focusing on the desired outcomes the performance measures can lend clarity to the purpose of actions of the agency and the functioning of the systems.

(f) Improvement over time: Performance measurements improve efficiency of the system over time when it is monitored over desired intervals.

The measurement of a system's performance is calculated by computing individual MOEs addressing specific objectives and systems.

An MOE is defined as a quantitative parameter used to measure the performance of a system or a facility. MOEs are performance indicators and characterize the different features and aspects of the system. Individual MOEs can contribute to its constant development and improvement when monitored

Over time, MOE's can be defined, identified, and gathered based on the needs and requirements of the agency maintaining the system, the data collected has to be analyzed to weigh the performance of the system. The obtained results would signify the impact of any traffic strategy that was employed. The MOEs can identify potential congestion points and help bring out improvements along that particular segment of road. Figure 2.1 illustrates the importance of performance measures in maintaining integrity of the system and also in improving overall system performance, particularly when the system provides basic utilitarian service.

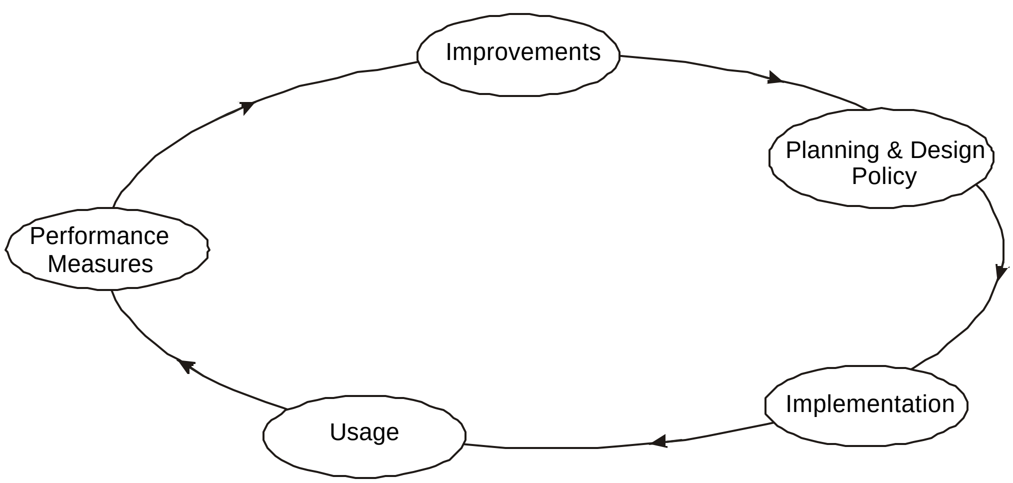

Figure 2.1 Performance Measurement Role for an Effective System

2.2 Individual Indictors of Performance

Individual measures are employed to quantify the effectiveness of a facility or a system. It is the individual performance indicators (MOE) that reflect the performance based on its objective and criteria.

Some of the characteristics of a good MOE:

- Tells about how well the system works
- Should be simple, logical and understandable
- Data collection should be easy and economical
- Shows trend
- Is timely

2.3 Criteria for Developing Measures of Effectiveness

The following describes the criteria consideration when developing MOEs.

(i) Relevancy to Objectives

Each MOE should have a clear and specific relationship to transportation objectives to assure the ability to explain changes in the condition of the transportation system

(ii) Simple and Understandable

In the constraints of required precision and accuracy, each MOE should prove simple in application and interpretation

(iii) Measurable and Quantitative

The MOEs should be suitable for application in pre-implementation simulation (have well-defined mathematical properties and be easily modeled) and post-implementation monitoring i.e., requiring minimum costs, time and staffing budgets for direct field measurements.

(iv) Sensitive and Broadly Applicable

The MOEs should be able to distinguish between relatively small changes taking place in the nature or implementation of the control strategy.

(v) Non-Redundant
The MOEs should avoid measuring an impact sufficiently measured by other measures.

(vi) Appropriately Detailed
The MOEs should be formulated to appropriate detail for the proper level of analysis.

The following describes the performance measures classified by their purpose and use.

a) Operational MOEs: These measures are used to determine the operational characteristics of transportation facilities such as freeway and arterials.

- Flow
- Average Speed
- Average travel time
- Number and percentage of stops
- Intersection Delay
- Queue length
- (v/c) ratio (volume to capacity ratio)

b) Planning measures: These measures are used in the planning operations of the systems:

- Acceptable delay (The threshold delay that the agency finds agreeable or that which doesn't necessarily harm the interests of public)
- Congestion Index (it is the ratio of total freeway delay to the freeway VMT)
- Travel rate (it is the ratio of travel time to segment length)
- Travel rate Index (it is the ratio of travel rate on a freeway or a arterial to the free flow travel rate)

c) Environmental MOEs:

- Vehicle emissions
- $(NO)_x$
- CO and $(CO)_x$

d) Economic MOEs:

- The cost of travel from origin to destination
- Maintenance and construction expenditures per vehicle mile traveled
- Economic cost of crashes
- Economic cost of lost time during incidents

e) Design MOEs:

- Free flow speed
- Density
- Intersection LOS

f) System MOEs: The system measures focus on the entire system to evaluate its effectiveness in terms of mobility, accessibility and utilization.

Mobility

- Origin-destination travel times
- Average speed or travel time
- Vehicle miles traveled (VMT) by congestion level
- Lost time or delay due to congestion
- Level of service or volume to capacity ratios
- Person miles of travel (PMT)

Accessibility

- Average travel time from origin to destination
- Average trip length

The above measures cover broad areas of the transportation system and network. [9] The performance measures that are used for evaluating various transportation systems are:

- Travel time
- Average Speed

- Throughput
- Number and percentage of stops
- Delay at an intersection
- Flow rate
- Density
- Queue length
- Throughput
- Vehicle miles of travel
- Person mile of travel

2.4 Description of MOEs

The typical MOEs identified above for various purposes are defined and described in more detail.

2.4.1 Travel Time

Travel Time is defined as the time taken to travel along a particular segment of a corridor or length of road, between points of known distance. Knowing the speed on the segment and the distance between known points, the travel time can be computed, which gives a view of the congestion conditions present on that highway. Travel time is a commonly used measure by various agencies. It gives an idea of the amount of time that will be spent during travel. The travel time measure can vary depending on whether stops or time spent in queues or under a certain speed are included or excluded from the travel time calculations. The typical calculation includes total travel time where delays are included. An example calculation of travel time on the freeway between TMS stations can be estimated by :

Travel time $t_i = (d_i)/s_i$ where d_i is the distance between the known points such as the detector station “i” on the road; s_i is the speed at the detector station “i.”

Travel time gathered over various segments of the freeway or road can be aggregated to obtain the total travel time across an entire or section of the corridor. The travel time can be estimated in five-minute intervals and provided on the Commuterlink website. Informing travelers of travel times allows commuters to make informed decisions about the travel.

T = $\sum_{i}^{n} t_i$ is the travel time across the corridor.

2.4.2 Average Speed

Average speed is one of the most widely used traffic measure to understand the effectiveness of systems employed for traffic management and control. It gives a direct indication of the movement of traffic flow on the roads. It is closely linked to travel times, but is a more direct traffic flow measure. System detectors placed on the roads provide the vehicle speeds. The average speeds of the vehicles when monitored over a period of time would help identify the potential congestion regions. The average speed of vehicles is more widely applicable as an MOE for freeways rather than for arterials. This is because large variations in vehicles speed on arterials occur due to interruptions in the traffic flow through intersections, accesses, merges and other driver behavior parameters. Consequently, average speeds can be used as a standard for measuring arterial effectiveness not by individual points but along an entire corridor. However, this means that manual corridor travel studies or GPS vehicles are necessary to identify this parameter on arterials.

2.4.3 Delay

Delay can be defined, as the additional time required traveling some distance due to impeding travel conditions on the road. Delay measures the degree of congestion indirectly by quantifying the difference in travel times between conditions that would have allowed free flow traffic and the existing traffic conditions. For freeways it can be computed by finding the difference in travel times with free flow speed and the actual speed between two know points. For surface streets delay, it can be measured by taking the difference in actual travel time and the acceptable travel time between two know points or stations.

The equation for travel time in existing traffic conditions is $T_o = D_d / s_o$

The equation for computed travel time with free flow speed or acceptable speed limit is $T_f = D_d / s_f$

Delay = $T_o - T_f$. This calculation determines delay over a particular segment of the roadway. Delay is a useful measure as it is relatively easy to compute in comparison with other MOEs. It is also widely used and appreciated by general public and can be compared readily with historic conditions to measure the temporal impact to a system.

2.4.4 Throughput

Throughput is the number of vehicles that can be accommodated by a section of the road. It is calculated by the ratio of vehicle miles traveled per unit time to vehicle hours per unit time. The throughput of the freeway system at any instant of time is the number of vehicles served per hour.

Throughput = (Speed/Segment length) * flow

The maximum throughput is given by

(Speed at Maximum Flow)/(Segment Length)*Maximum flow.

The throughput is useful for overall efficiency of a freeway system by finding the ratio of the actual throughput to maximum throughput. Throughput is a good measure for normalizing other MOEs. For example, if historic tracking of signal timing delay performance on an arterial shows that delay has increased by 5 percent, knowing that the throughput had increased by 15 percent would be important to drawing conclusions about the systems performance.

2.4.5 Number and Percentage of Stops

Percentage of stops reflects the quality of the transportation service available to the users. The time spent by a road user generally increases with every stop encountered. Restriction to the movement of the vehicle could be due to vehicle stops at signalized and un-signalized intersections, due to incidents or due to heavy traffic flow on the road. The greater the number of stops along a corridor, the greater the travel time and delay will be, decreasing mobility. Along a surface street, the percentage of stops generally represents the density of intersections or traffic signals along a corridor and reflects interruptions caused to the smooth movement of traffic. It is computed as the percentage of the number of intersections per mile along a corridor. For uninterrupted roadway systems such as freeways, the number and percentage of stops indicate the degree of congestion present.

2.4.6 Intersection Delay

Intersection delay reflects the signal throughput and measures the vehicle delay at a traffic signal. The intersection delay is computed using the HCM method and is given by $\mathbf{d = d_1 + d_2 (PF) + d_3}$

where:

d_1 = uniform delay component assuming uniform arrivals, sec/veh

PF= uniform delay progression adjustment factor that accounts for the effects of signal progression on delay;

d_2 = incremental delay to account for random and over saturation queues, adjusted for the duration of analysis period and the type of signal control;

d_3= residual demand delay to account for the over saturation queues that may have existed before the analysis period, sec/veh.,

Uniform delay, d_1

Uniform delay is a delay estimate for uniform arrivals and stable flow. It is given by d_1 = $\frac{0.5C(1-g/C)^2}{1-\min.(1,X)g/C}$ where C is the total cycle length of the signal in secs, g is the effective green time for the lane group and X= v/c ratio or the degree of saturation for the lane group.

Progression Adjustment Factor: Indicates the proportion of vehicles arriving on green at the signal. Good signal progression will result in high proportions of vehicles arriving on green. Poor signal progression will result in a low percentage of vehicles arriving on green or a high percentages coming to the signal on red. Progression Factor (PF) = $\frac{(1-P)f_p}{1-(g/c)}$ where

P = proportion of vehicles arriving on green

g/C = proportion of green time available, and

f_p = supplemental adjustment factor for when the platoon arrives during green.

Incremental delay d_2

Incremental delay estimates the delay due to non-uniform arrivals and temporary cycle failures as well as those caused by sustained periods of over saturation. This delay is sensitive to the degree of saturation (X), the duration of the analysis period of interest (T), the capacity of the lane group (c), and the type of signal control as reflected by the control parameter (k). The formula assumes that there is no residual queue at the signal.

$$d_2 = 900T\left[(X-1)+\sqrt{(X-1)^2+\frac{8kIX}{cT}}\right]$$

where:

T = duration of analysis period, hours;

k = incremental delay factor that is dependent on controller settings;

I = upstream filtering/metering adjustment factor;

c = lane group capacity, vph and

X = lane group *v/c* ratio or the degree of saturation

Residual demand delay (d_3)

Residual demand delay is due to the delay caused by the residual queue, which has not been serviced by the intersection in the previous cycle.

2.4.7 Queue length

Queue length reflects the level of road congestion, particularly on arterials and at ramp entrances. Queue length is the number of vehicles waiting for the right of way at an intersection for a given movement.

There are 10 accepted HCM methods for computing queue lengths in under saturated conditions. ITE recommends the Poisson distribution queue calculation (either the 90^{th} or 95^{th} percentile) for signalized intersections. AASHTO recommends the two-minute rule at unsignalized intersections for estimating left turn storage needs. These are both more common methods used in practical implementations. Even UDOT has a rule of thumb for left turn queue needs at signalized intersections, one foot of storage for each vehicle during the peak period. If a left turn demand of 300 vehic les per hour was estimated, then 300 feet of storage should be provided.

CHAPTER 3. LITERATURE REVIEW

This research is largely supported by the relevant literature study. The literature study includes existing systems, input devices, instruments, and available algorithms that help dynamically compute identified common measures of effectiveness. This literature study reviews common performance measures and the individual MOEs, which have been widely accepted and used by various DOTs across the country. This search also ventured into the various input devices, which would be required to obtain a particular measure. An attempt to address the following critical issues provides the foundation for this research:

- The MOEs commonly applied for obtaining the effectiveness of ATMS components
- The input devices used for the calculation of performance measures.
- The acceptability and the conformability of the MOEs to UDOTs requirements: this further depends on the type and format of the data coming into the UDOTs TOC and intervals in which they are being received.
- The recommended measures of effectiveness for each component of the ATMS.

3.1 California's Performance Measurement System

Pravin [3] describes how Caltrans is using a Performance Measurement System (PeMS) to monitor and report routine congestion on California's roadways. The Caltrans PeMS collects and stores data from loop detectors and converts this data into information, which is useful and accessible to Caltrans personnel. The PeMS can generate charts and reports summarizing traffic conditions, which help engineers and planners to locate congestion areas and identify possible solutions. The information obtained by the PeMS reflects the system performance and aids in enhancing the freeway systems productivity.

The PeMS software is designed to work on the real time data and compute:

- Aggregate 30 second values of flow and occupancy lane by lane
- speed for each lane
- Compute basic performance measures such as congestion delay, vehicle-miles of travel, vehicle-hours traveled and travel times.
- Maximum throughput for each segment along the freeway from the speed and volume data

The software also generates reports and graphs to assist in the travel times and to find potential bottlenecks along the freeways. The PeMS generates the contour plots when a freeway section along with a performance variable such as speed, flow or delay is selected. An anomalous performance by the contour map would indicate the presence of an incident or reveal potential congestion points.

The PeMS finds application in estimation of future travel times based on current and past travel times. According to Pravin [3], an advanced PeMS application can calculate potential reduction in congestion by an ideal ramp metering policy on a freeway section that experiences recurrent congestion during the peak hours of traffic. It also can help planners identify locations that could benefit from ramp metering. Since the application also calculates the ramp queues it also checks if the ramp storage is sufficient. PeMS helps study HOV lane effectiveness through data collected on the HOV lanes. The PeMS system works offline i.e it collects and archives data from which various graphs and reports are queried. The PeMS provides a basis for combining the MOEs algorithms into a single program having the capabilities of evaluating various sub systems.

3.2 Portland's Traffic System Performance Evaluation System

The *City of Portland's Traffic System Performance Evaluation System* [11] uses five performance indicators to study effectiveness of its transportation system. Each of the five indicators addresses a specific system objective. *District accessibility* measures the accessibility and ease of movement in the region. The *street origin-destination characteristics* measure the non-local trips on streets with different functional classifications. Apart from travel time and average speeds a *multi-modal level of service* assesses the degree of service obtainable from the system. The literature also shows that travel time and speeds can be used as performance gauges to measure the ATMS effectiveness.

3.3 Real Time Information Processing Algorithm

Leonard, Ramanathan and Recker [12] have developed an algorithm to assess the performance of systems of coordinated and uncoordinated traffic actuated controllers in real time. This algorithm is based on the macroscopic, platoon-based traffic flow for online evaluation. The information after the evaluation is sent back to the TOC for further investigations. The paper focuses on development of a simulation model using the algorithm for evaluation of the traffic controllers. The algorithm is based on macroscopic traffic variability and considers the relationship between upstream traffic flow and downstream flow described by platoon dispersion. The model is represented as $Q_{t+T} = F*q_t + [(1-F)*Q_{t+T-1}]$ and is tested in TRANSYT-7F simulation software; where Q_n is the downstream flow at timestep n; q_n is the upstream flow at timestep n; T is 0.8 times the cruise travel time on the link, expressed in terms of timesteps, F is the smoothing factor, calculated as $1/(1+\alpha T)$ where α is a platoon dispersion factor. The measures of effectiveness that are employed include degree of saturation, maximum back of queue or queue length, the number of stops. Uniform delay i.e., the delay due to the vehicle's arrival at the back of the queue, and random delay (delay due to congestion) also are used to measure the ATMS effectiveness. The algorithm is presently undergoing continuing research and is specific as it only evaluates the coordinated and uncoordinated actuated traffic controllers.

Therefore travel time, delay and queue length are significant MOEs, which are used widely by different agencies and help in measuring overall the performance and effectiveness of the ATMS system.

The literature search for any existing model that dynamically computes MOEs for ATMS has not produced a commercial product or ongoing research in this area. The only exception is the Commuter Congestion Algorithm (CCA) developed for arterial monitoring at the University of Utah. CCA automatically computes the level of service of arterials in five-minute intervals, given the green time, the occupancy of the vehicles at the intersection. The CCA can be directly implemented as a measure for the arterials. The idea of real time MOE for ATMS appeared new and innovative to most DOTS' when they were contacted for information. The procedure followed by them is to collect the required traffic variables needed for computation of various measures and then evaluate the system performance offline. On-line measure, aside from direct speed measures, seem a unique concept.

Among the papers that describe dynamic computation of a MOE queue length estimation algorithm designed for a responsive real time signal control system. The queue length is calculated based on the detector counts, occupancy and motion properties of vehicles traveling on a signalized approach and on the knowledge of the varying signal state. The algorithm is supported in WATSim micro simulation model and was interfaced with RT/IMPOST control policy. This paper demonstrates the computation of queue length in real time and hence it is incorporated in this research as a potential MOE that can be found dynamically in real time to assess the performance of a particular intersection.

The cost of congestion and the percent of congestion depend on the total travel during periods of congestion. Percentage congestion refers to the proportion of the journey that has increased the total travel time. The performance measures used in the Urban Mobility study [6] need input data ranging from several months to several years. Also the measures adopted are more applicable for a system evaluation study rather for a dynamic data analysis.

Several DOTs were approached to identify the MOEs used by each for studying the effectiveness of their ATMS components. The DOTs that were approached were the WSDOT, MnDOT, CALTRANS, GDOT, IDOT, WDOT, KDOT, VDOT, MDOT, ODOT, and FHWA.

The DOTs had some common operational MOEs for understanding efficiency of the system. They applied some measures, some of which were commonly applicable to a wide variety of transportation systems like the travel times and delays, while others were more specific to their objectives and goals.

3.4 Urban Mobility Report 2001

The Urban Mobility Report 2001 [6] of the Texas Transportation Institute has quantified 68 areas in the country based on mobility available to traveling public. It has applied mobility measures such as travel time index, delay per peak road traveler, and cost of congestion, change in congestion, and percent of congestion. Travel time index is an indication of the congestion present on the roads. It is the ratio of the travel time during congested conditions to the travel time during free flow conditions. Travel rate is defined as the ratio of the travel time during peak conditions to the travel time during free flow conditions.

The mobility report has quantified congestion existing on the roads across the country with the help of various state transportation agencies such as California DOT, Colorado DOT, New York DOT, Oregon DOT, Florida DOT, Kentucky DOT, Virginia DOT, Maryland State Highway Administration, Texas DOT, Washington DOT, and Minnesota DOT. It identifies the present congestion based on mobility available on roads and highways using measures, such as travel rate index, travel time index, corridor mobility index, and delay ratio. It shows potential congestion and prevailing congested road conditions, then quantified them based on the level of congestion present. An example of the travel time index is shown below.

$$\text{Travel Time Index} = \frac{\left(\dfrac{\text{Freeway Travel Rate}}{\text{Freeway Free - Flow Rate}} \times \text{Freeway Peak Period VMT}\right) + \left(\dfrac{\text{Principal Arterial Street Travel Rate}}{\text{Principal Arterial Street Free - Flow Rate}} \times \text{Principal Arterial Street Peak Period VMT}\right)}{\left(\text{Freeway Peak Period VMT} + \text{Principal Arterial Street Peak Period VMT}\right)}$$

Table 3.4-1 highlights the MOEs that are sensitive to specific ITS strategies [5]. Some of the MOEs require historical data for particular period of time and hence they cannot be converted into real-time measures, but are appropriate for archival processes and determining system variability and reliability.

Table 3.4-1 ITS Strategies and Measures of Effectiveness

ITS Strategies	Measures of Effectiveness
Ramp Metering	▪ Average speed on the freeway ▪ Average speed on arterial streets ▪ Delay at ramp meters ▪ Average queue length at metered ramps ▪ Number and severity of accidents ▪ Number and severity of other incidents ▪ Public reaction
Traffic Control System	▪ Average speed ▪ Traffic volume ▪ Number of stops ▪ Average vehicle delay at signals ▪ Number and severity of accidents ▪ Number of special events, construction/maintenance, incident applications of the system
Incident Management	▪ Incident detection/verification time by incident type/severity ▪ Incident response time by incident type/severity ▪ Incident clearance time by incident type/severity ▪ Time periods and locations of incident occurrences
Regional Traveler Information System	▪ Origin to destination trip time ▪ Amount and sources of information received ▪ Frequency of route diversion ▪ Frequency of trip time changes
Freeway Control	▪ Average speed on freeways ▪ Traffic volume ▪ Travel time within a corridor ▪ Level of service

Table 3.4-2 summaries the MOEs that were identified for automation to compute the performance characteristics of various ATMS subsystems.

Table 3.4-2 MOEs identified for automation

ATMS Component	Individual MOE	Input	Output
Freeways	➢ Travel time ➢ Delay ➢ Speed ➢ Flow rate	Detector spacing Avg. speed at the detector Free flow speed/posted speed	Travel time in seconds Delay in five-minute intervals
Ramp Metering	➢ Ramp Queue ➢ Ramp delay ➢ Spare Freeway Capacity	Detector data including occupancy, freeway speeds, volumes	Queue length in seconds
HOV lanes	➢ Travel Time Savings ➢ Relative differences in speeds ➢ Person occupancy rates ➢ Violation rates	Speed data on different lanes Distance between detectors Speed data Vehicle occupancy data	Congestion levels based on travel time savings Speed differences
Arterials	➢ Intersection LOS ➢ Queue length	Volume, speed, occupancy, signal timing, detector distance	(v/c) ratio in five-minute intervals The number of vehicles awaiting green

CHAPTER 4. ATMS BACKGROUND

ATMS can be defined as computerized communications system that incorporates traffic surveillance and management, incident detection and information dissemination to public. ATMS constantly surveys traffic conditions through in-field detection devices. This information is useful for on-line processes, such as identifying possible incident locations and freeway congestion conditions. The information also is useful for off-line functions, such as surface street traffic control or identifying bottleneck locations.

4.1 Objectives of ATMS:

- ATMS provides capabilities for integrated, dynamic, real time, and proactive traffic management to combat congestion and optimize traffic operations.
- ATMS ingests and processes data from advanced sensors over wide area networks, including data from new types of sensors, alternative technology sensors and probe vehicles.
- ATMS will supports detection of and rapid response to incidents and collaborative action on the part of various organizations to provide integrated responses.
- ATMS will enhance the safety of operations in a traffic network.
- ATMS will provide information and functional capabilities to accommodate multi-modal transportation management strategies
- ATMS will support the maintenance of the transportation infrastructure.

ATMS provides the following benefits:

- Increases safety
- Reduces delays
- Reduces fuel consumption
- Improves air quality

- Improves transportation system capacity

To understand how effectively a system is performing it has to be subjected to a test of performance measures. The performance measures can assess the functioning of the system, identify any anomalies in the system and recommend for its repair or replacement.

ATMS is a combination of surface street signal control management, freeway traffic management, and traveler information distribution. Surface street signal control systems consist of the remote surface street signal control system. The freeway management is composed of freeway control, HOV lane management, ramp metering, VMS and HAR. Figure 4.1-1 shows a context level diagram of the ATMS. Figure 4.1-2 shows a generic ATMS structure diagram.

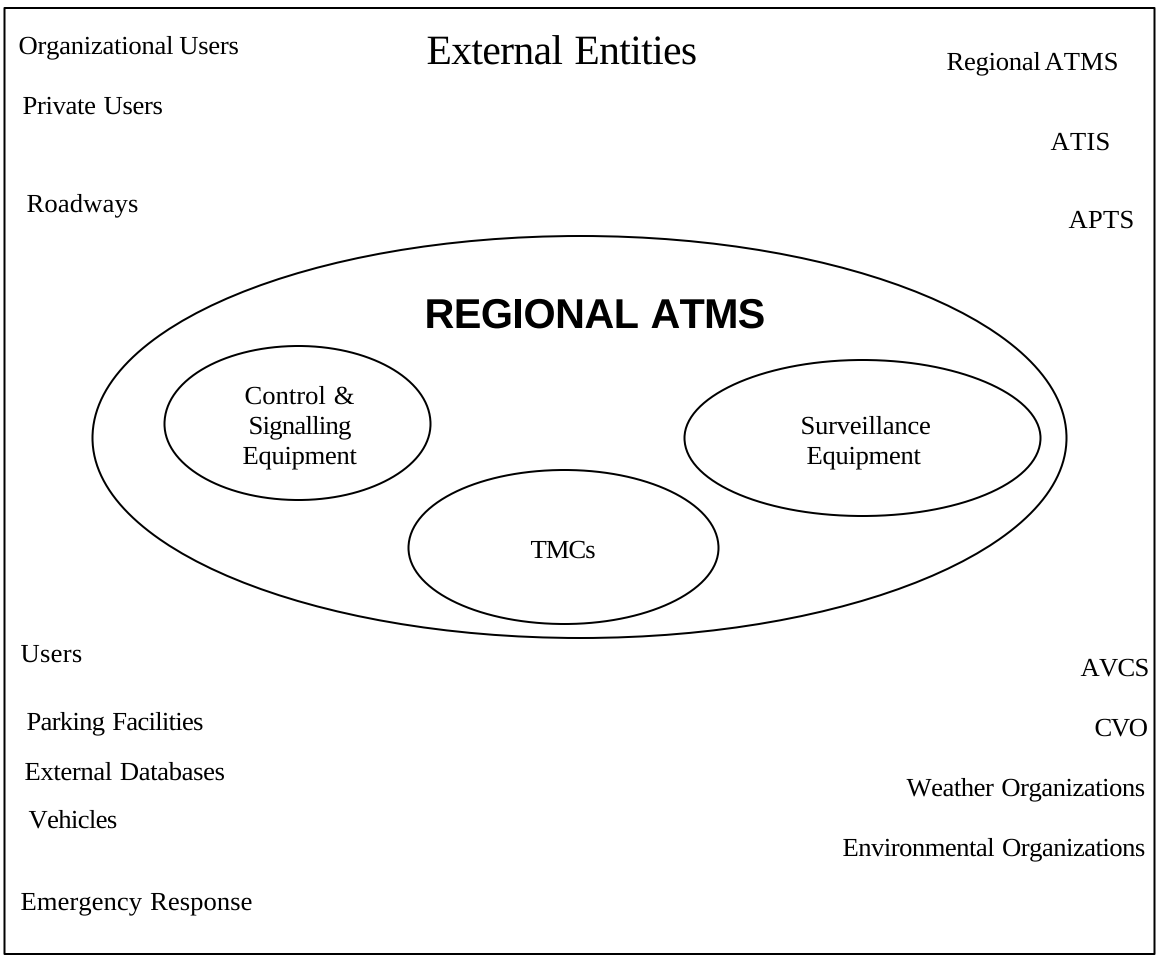

Figure 4.1-1 ATMS Context Level Diagram

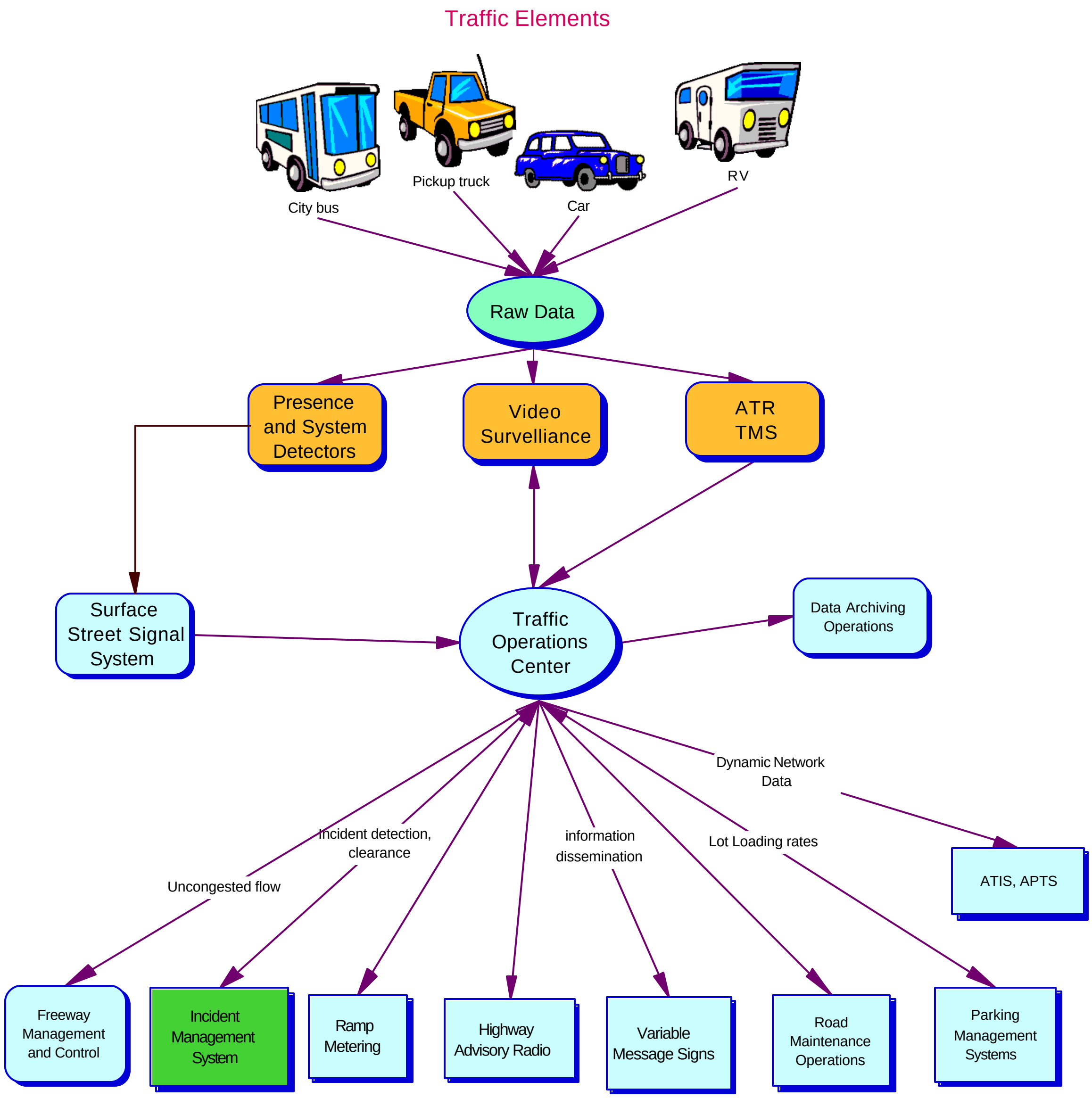

Figure 4.1-2 Generic ATMS structure

CHAPTER 5. INDIVIDUAL COMPONENTS

The following section describes the recommended process for applying the raw data available from ATMS field devices and calculating MOE for the individual ATMS components.

5.1 Arterials

Arterials, also known as surface streets, provide the basic transportation service to people in a community, town or city. They form the internal roadway network that provides the essential transportation to people in a community, town or city.

The signal system on the arterials maintained by UDOT recently has been updated with many coordinated corridors running on actuated-coordinated control. The actuated-coordinated philosophy is a coordinated bandwidth is defined on the main street. The side street then is assigned a non-coordinated portion of time for its operations. However, any unused portion of the side street green time is returned to the main street in the form of early green. While this provides more green time for the main street and thus increases its capacity, it has a negative impact on main street coordination. There also are some minor intersections that operate as semi-actuated or fully actuated. Although communication from the TOC to the signal controllers allows for signal timing updates, there is no feedback from the field to the TOC that indicates how well the signal is operating. Little information about surface street congestion is available at the TOC. Therefore, changes to signal timing during high congestion or incidents is inefficient at best. Much more emphasis is necessary in providing more surface street system detectors and developing methods to incorporate these system detectors into usable information for assessing the current state of the surface streets.

The common measures that can be used for computing effectiveness of the signal are the intersection Level of Service (LOS) or volume to capacity ratio (v/c), maximum throughput and queue length. Intersection LOS can be obtained in real time with the volume and occupancy data feeding from the system detectors to the traffic controller. The traffic controller extends the green time for that direction of movement based on the demand volume along that direction. UTLs CCA dynamically compute the intersection LOS based on the capacity calculation and the volume it receives from the system detectors. The algorithm computes the saturation flow on the arterial per lane per five-minute interval based on the volume and occupancy from the system detectors and the green time and cycle length provided from the traffic controller. Figure 5.1-1 shows a method for estimating queue lengths at signalized intersections and Figure 5.1-2 shows the CCA, which identifies intersection congestion as a function of capacity utilized.

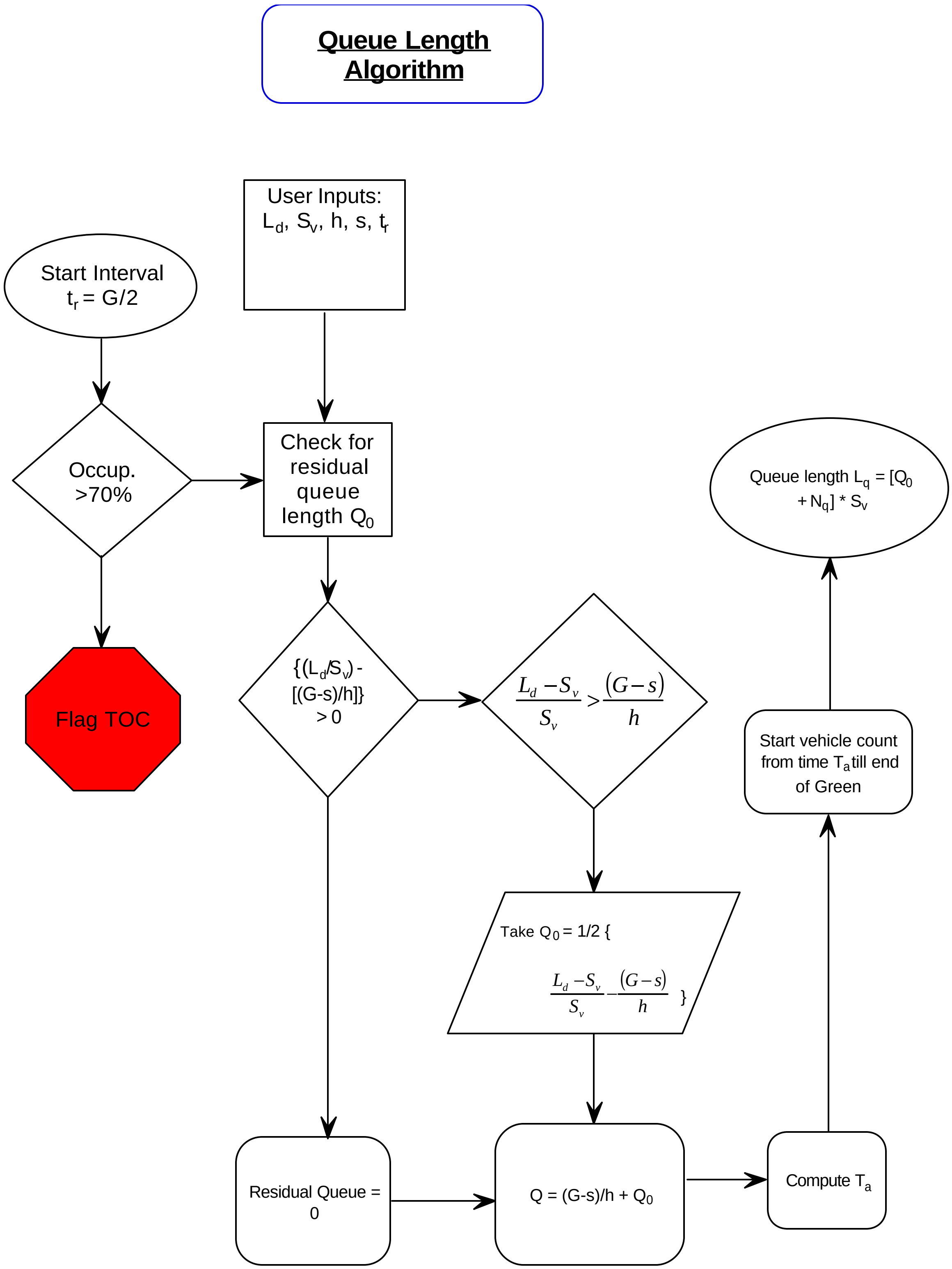

Figure 5.1-1 Queue Length Algorithm

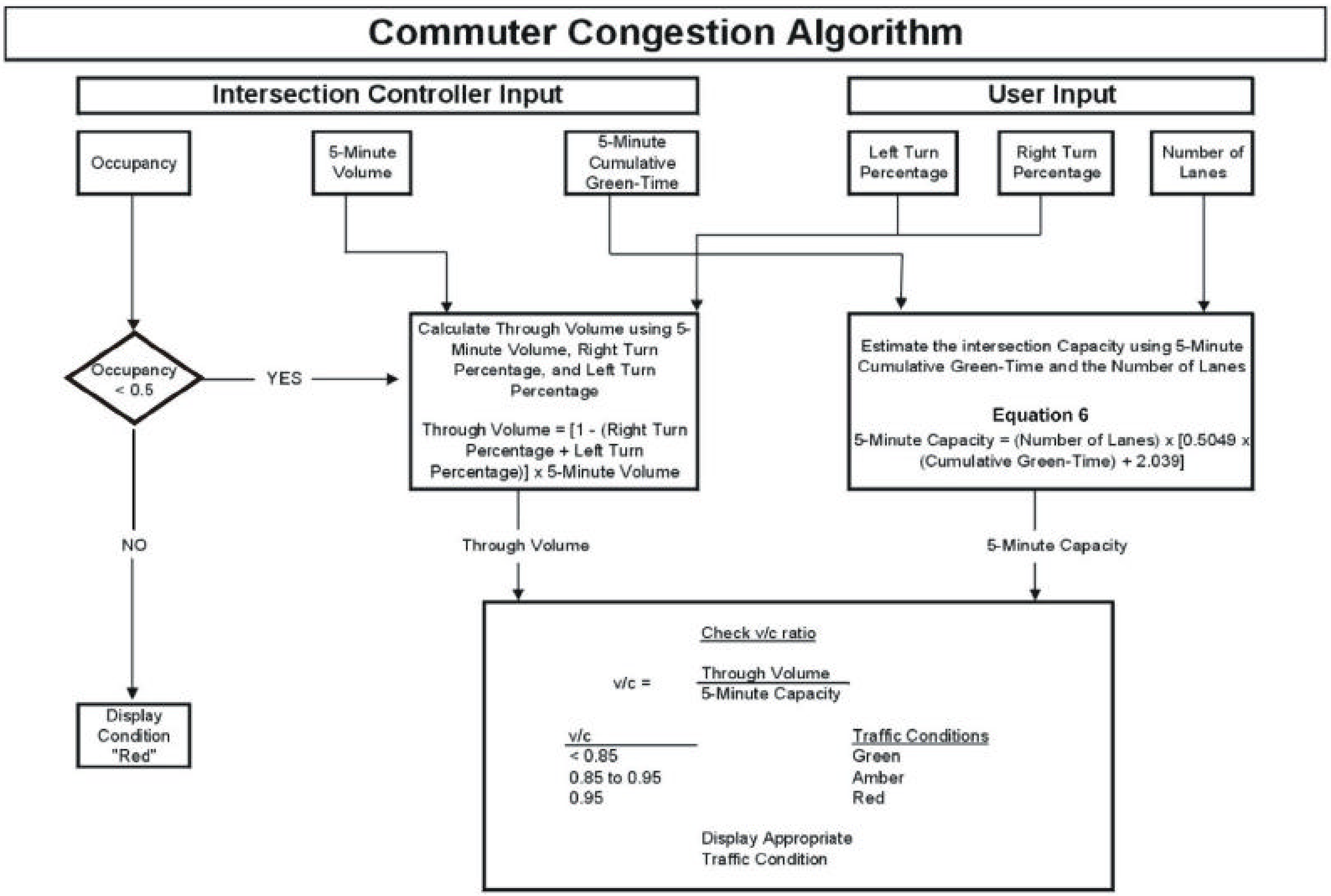

Figure 5.1-2. UTLs Commuter Congestion Algorithm.

5.2 Freeways

5.2.1 Freeway Management Control

The freeway management control is intended to reduce congestion and delays on the freeway, by detecting incidents and providing consistent surveillance and management of traffic using automatic traffic detectors, road-user input (cellular phone input) and video observations. This allows a timely response to congestion. Components of the freeways management include not only the general-purpose lanes, but also HOV lane management and ramp metering. Freeway effectiveness can be measured by average speeds, the travel time, and density experienced on the freeway.

Travel time or speed is the primary indicator of congestion present. If the travel time is higher than the acceptable or expected travel time as fixed by the agency for the particular route, then the difference between the actual and the expected travel times would determine the level of congestion that is present in the form of delay on that particular segment of the freeway. Travel times considered during the peak periods of the day would give a more realistic assessment of the traffic conditions prevailing on the road.

5.2.2 Input Devices

System detectors and loop detectors can be used to derive the input variables involved in obtaining travel time. These detectors record speed, occupancy, volume in intervals defined by the TOC. To obtain the travel times, distance between the detectors along a corridor and the speeds are required in intervals of about five minutes.

5.2.3 MOEs applicable for Freeways

The HCM uses “density” as the service measure for computing the level of service on freeways along with speed and volume as secondary measures. The HCM method of computing density is tied with free flow speed and the saturation capacity of the lane. The saturation capacity of the freeway lane depends on a number of baseline and driver behavior characteristics, making density a difficult real time measure.

Travel time is a more appropriate measure for the freeways, since freeways don't have any roadway interruptions, such as signals. Travel times and speed information are widely understandable by a broad range of audience and has a wide range of uses. An aggregation of travel times along various segments of the corridor provides the "corridor travel time." Corridor travel time can be defined as the time taken to travel through the corridor. The average speeds along the corridor can also be represented in a speed chart indicating the different regimes of speed.

5.2.4 Freeway Delay Algorithm

The freeway delay algorithm, shown in Figure 5-2-1, addresses the difference between the free-flow speed and the actual measured speeds. Delay is the time loss due to the lower-than-free-flow speed over a given distance.

Freeway Delay Algorithm

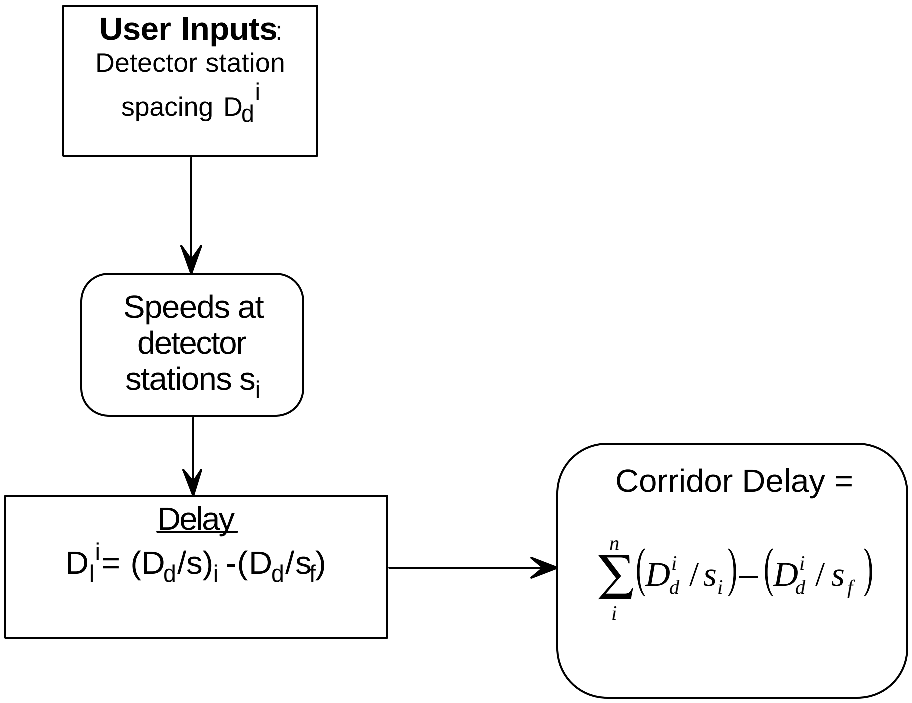

Figure 5.2-1.Freeway Delay Algorithm

An example of the average speeds on the I-15 corridor is shown in Figure 5.2-2. The blanks indicate the absence of data from collection devices.

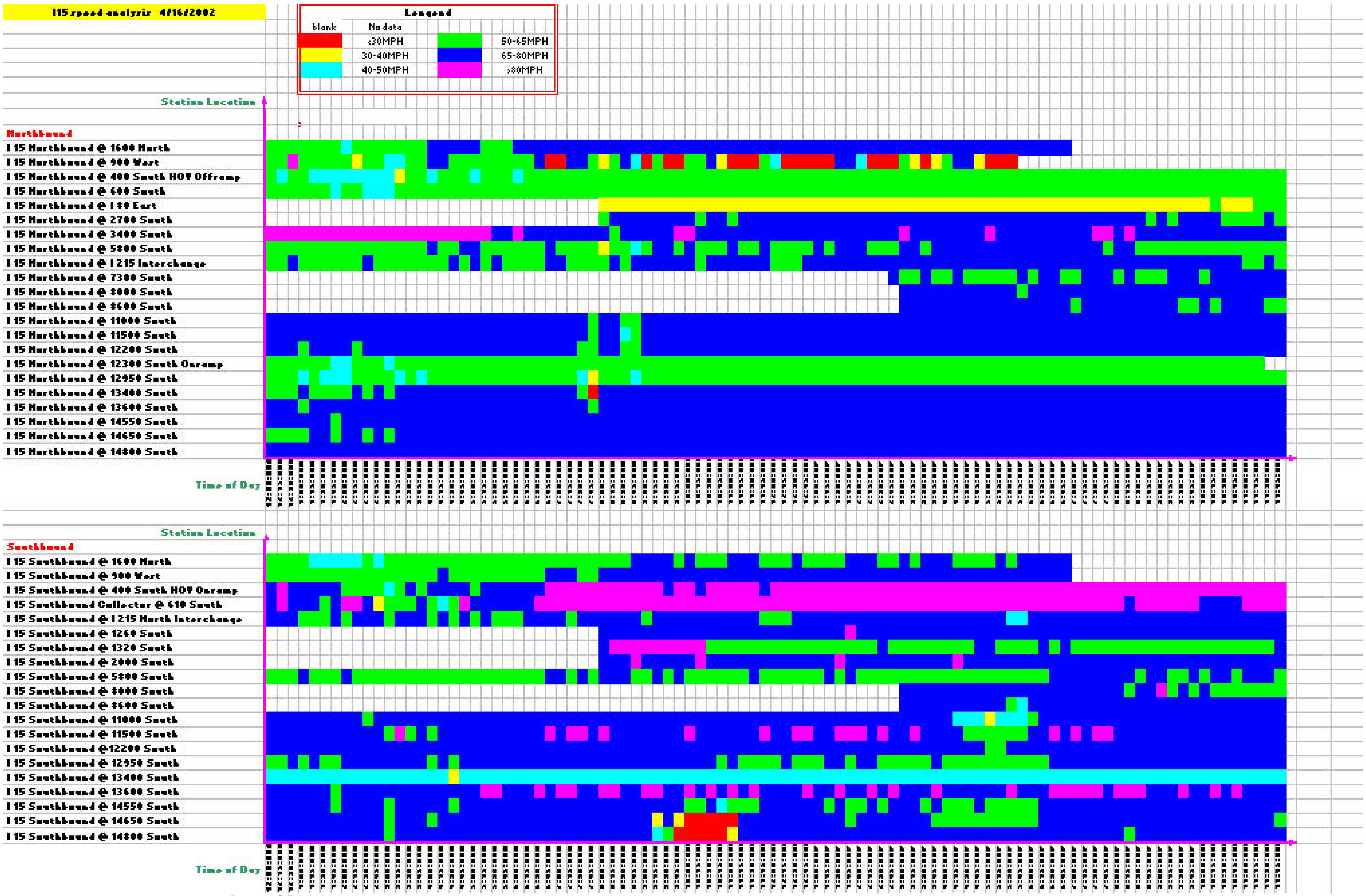

Figure 5.2-2: I-15 Speed Profile

5.3 HOV Lanes

HOV lanes are exclusive lanes provided for higher occupancy vehicles and transit. The concept of HOV lanes is to encourage car pooling, traveling of more than one passenger per vehicle on the road. This in turn results in the movement of less number of vehicles, but the same number of person-trips and reduces congestion. Travel by HOV lane reduces travel time due to lower vehicle demand relative to the general-purpose lanes and can result in substantial travel time saving. There are many measure of effectiveness that can determine whether HOV systems meet their goals and objectives. Some of the DOTs use person throughput, average speed on HOV lanes, travel times, average lane occupancy and violation rates as common MOEs.

The Texas Department of Transportation [8] has quantified HOV lanes by the amount of travel time saving made by HOV lane users relative to those on other lanes of freeways. The travel time savings directly depended on the level of congestion present on lanes adjacent to the HOV lane.

The travel time savings is the reduction in the amount of time observed between the travel time of a vehicle using HOV lane and a vehicle using a normal lane.

Travel time saving = (Travel time in HOV lane) – (Travel time in other lanes)

Figure 5.3-1 shows a general freeway configuration with HOV lanes location on the inside lane, as with the I-15. Figure 5.3-2 shows the HOV travel time savings algorithm and a functional diagram for data needs and calculation.

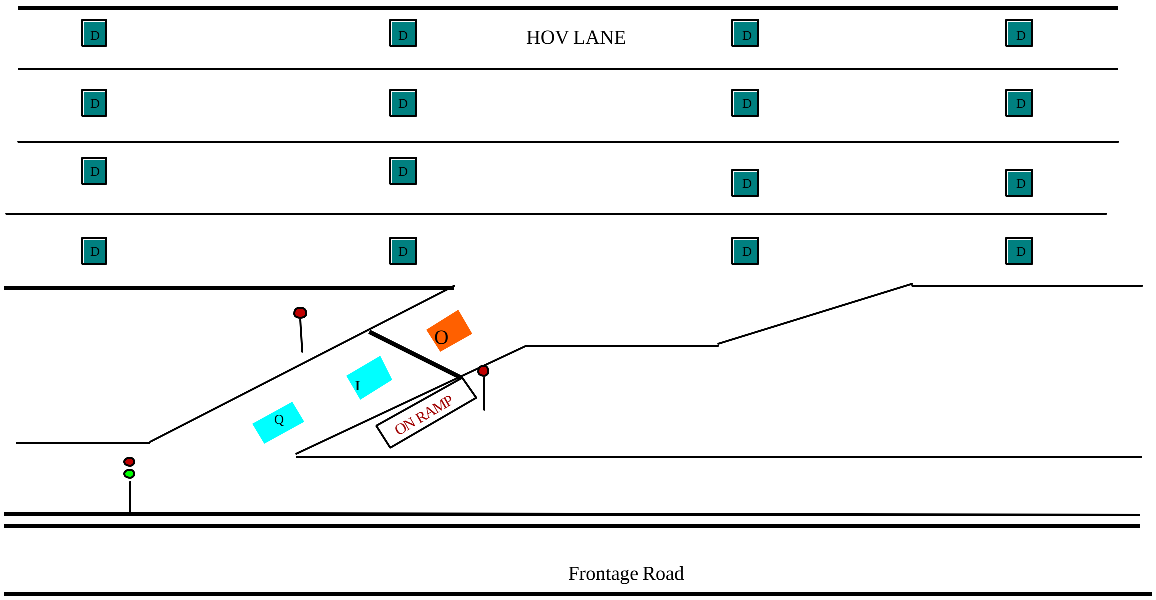

Figure 5.3-1. Freeway lane Configuration with HOV lane

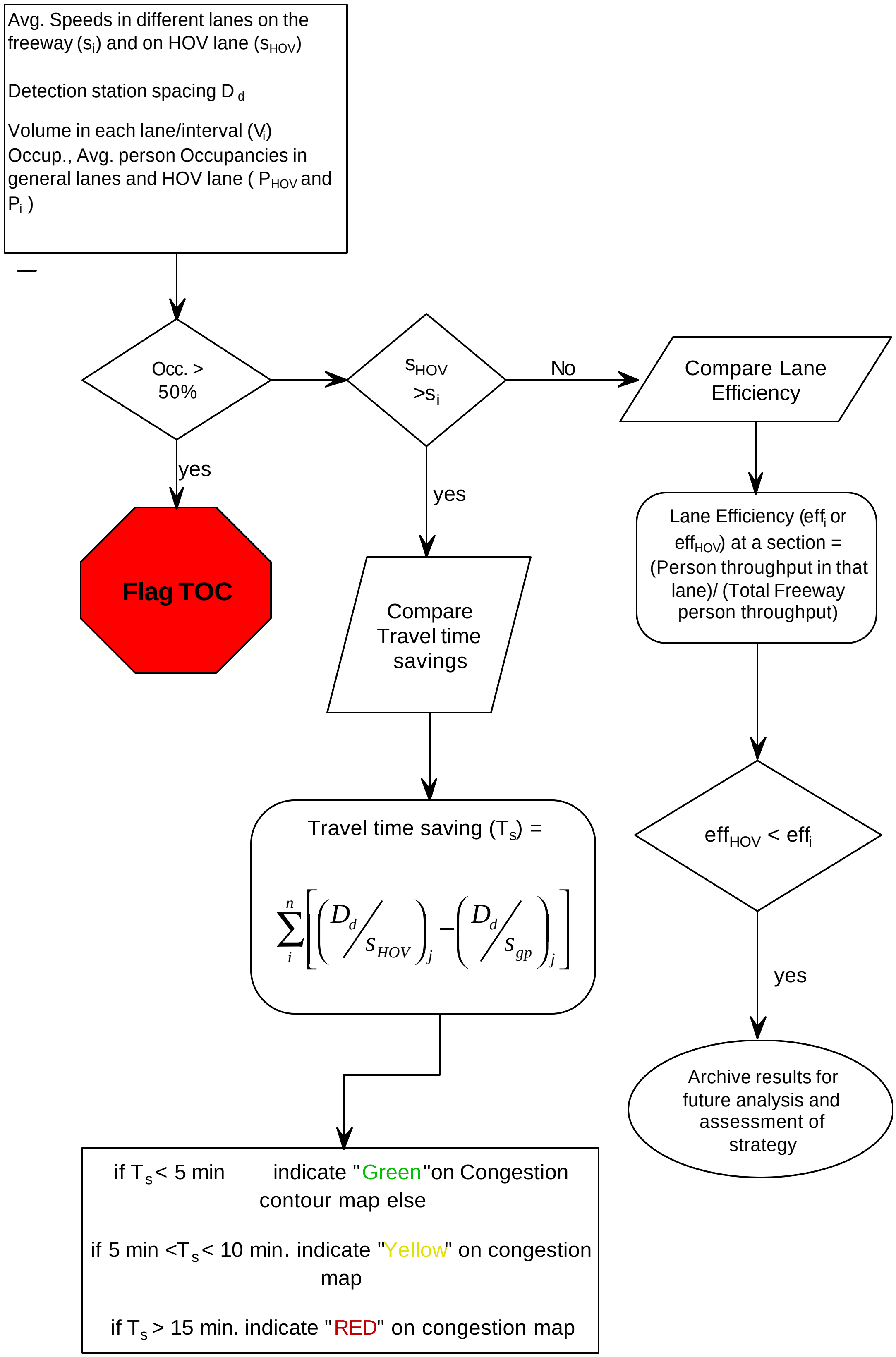

Figure 5.3-2. HOV "Travel Time Saving Algorithm"

5.4. Ramp Metering

Ramp metering is control strategy used to reduce congestion, reduce incidents and to maintain the stability of flow on freeways. Ramp metering is employed when there is large demand for entrance on to the freeway and the freeway operates at close to capacity. When ramp metering is activated, the metering allows only one car per every green signal on to the freeway. This limited access to the freeway maintains the flow on freeway and also reduces the probabilities of an incident, since interchanges are potential zones of hazard. By controlling entrance vehicles, the freeway speeds can be maintained, but at a risk of ramp queuing that might spill to adjacent arterial intersections.

The MOEs for ramp metering are the spare freeway capacity, total delay at the ramps, queue length, and average speed on the freeway at the merge areas.

(i) Spare Freeway Capacity is the number of vehicles that can be served by the freeway demanding access through on-ramps. The spare freeway capacity is the difference between the capacity of the freeway at that section and the demand volume that is entering the freeway and indicates the additional number of vehicles that can be served by the freeway. The demand on the ramp is obtained from the ramp detector, which gives the volume for a particular interval of time.

(ii) Ramp Delay

The efficiency of the freeway also is determined by the amount of delay experienced by the vehicle waiting for an access to the freeway. This delay would be the same as the control delay experienced at intersections of surface streets. When ramp metering is in operation, then it only allows one vehicle per every green given by the signal. Ramp metering regulates the demand that is seeking an entry and there by stabilizes flow of traffic on the freeway. The ramp metering policy is activated when the demand exceeds the spare capacity on the freeway endangering smooth flow and creating bottleneck conditions.

(iii) Queue length

Ramp queue length gives a measure of the effectiveness of a signal and the congested conditions on the road. It also provides a measure of storage demand, which can be compared, to available storage and then spillage onto arterials can be monitored.

5.5 Variable Message Signs

Variable Message Signs are used in a variety of situations, all of which involve the display of real time information for the benefits of motorists. Some of the instances where the VMS supports information dissemination:

- Non-recurrent events related to incidents on or around the roadway. Incidents may include breakdowns, vehicle disablements or crashes, hazardous material spill over, etc.
- Scheduled non-recurrent events with capacity reduction
- Scheduled non-recurrent events without any capacity reduction
- Environmental problems due to hazardous weather conditions (heavy fog, snow, etc)
- Scheduled recurrent event (roadway maintenance or construction)

The purpose of VMS is to reduce delays during above instances and help provide efficient travel conditions to the motorists. The effectiveness of the VMS can be gauged from amount of time saved by obeying the sign or the number vehicle using the VMS disseminating information. The percentage based on the vehicles using the VMS would relate the effectiveness of the VMS in disseminating the information to the road users. This would include a much more detailed modeling and manual survey effort. A license plate survey during known incidents would be an excellent method for quantifying this factor. However, an automatically measured or calculation based approach would be difficult without GPS probe vehicles travel through the incident area.

MOEs for VMS:

- Estimated Travel time saving = (Travel time without obeying/use of VMS) – (Travel time utilizing VMS)

- % of the conforming to VMS information dissemination = {(no. of vehicles obeying VMS)/ (total no. of vehicles)}* 100.

5.6. Wide Area Video Monitoring System

Video monitoring is part of the surveillance system of the ATMS and involves sophisticated electronics and machine-vision technology to continuously monitor the field disturbance caused by the movement of traffic. It captures moving images, analyzes them and transits them back to the command center. The command center (TOC) which, monitors the traffic condition would address any unusual circumstances such as incidents, high congestion or instability in flow by directing the incident management team or displaying messages through VMS or informing the riders through the HAR. The system proves advantageous in places where long distances need to be under surveillance such work zones or along stretches of road of recurrent congestion. This system complements the detection provided by in pavement sensors, which at times are prone to error and are low in reliability. Also the video monitoring systems generally don't have problems of lost communications with the TOC as frequently happens with detector stations hampering monitoring and provision of efficient and reliable traffic management services by ATMS. The system when fully integrated provides the data to better manage traffic using machine vision technology.

The system also can be used to obtain real time traffic data without the use of in-road detectors using the machine vision processor that captures, stores, analyses, and records basic traffic characteristics such as volume, speed, and occupancy. The detection systems, such as Peek or Autoscope or others, can be used to monitor freeways, highways and arterials. Atlanta's new ATMS monitors the flow of traffic along Interstates 75 and 85 in real time using the wide area video detection systems. The video information captured by the cameras is sent to TMC through a network of integrated fiber optic cables. The operator at the TMC then changes the images and analyses them for possible signs of congestion and incidents. The visual information and the processed data are helpful in the decision making process. The processed data is most valuable to the traffic engineers for making operational decisions. The visual pictures are valuable for the TOC operational engineers and the commuters. UDOT's Commuterlink post the camera pictures on the web. Commuters prior to their trip can access this so they can make route choice decisions based on the information available. In this ATIS role, "a picture is worth a 1000 words."

5.6.1 Machine Vision Processor

The machine vision processor (MVP) is the core component of the wide area video detection system. The MVP stores, retrieves, and analyses the data that is being captured by the cameras. The MVP also is responsible for sending an alert signal to the TOC personnel in case of congestion. On a surface street application, the MVP directs the signal traffic control system to change its signal or signal timing accordingly to accommodate the varying traffic conditions.

The detection system uses virtual detectors to collect traffic data. The key detectors for freeway applications count, measure speed, determine vehicle length, indicate stopped or wrong way vehicles, and accumulate traffic statistics for later retrieval by the central communications server.

The detectors are drawn on a live video image or a bitmap snapshot of the video image. The detectors can be easily edited for changing traffic patterns or optimizing performance. This feature proves beneficial in cases when modifications are made to existing lane layout on the road such as during construction. Personnel at the TMC can easily adjust the detector layout from a PC rather than incurring the expenditure of the installation new detectors inside the pavement. Figure 5.6-1shows the Video Detection System configuration with video cameras providing information to the processor and into a database for storage. Figure 5.6-2 shows the machine vision processing procedure for congestion/incident monitoring. Figure 5.6-3 shows virtual detector arrangement on a freeway image.

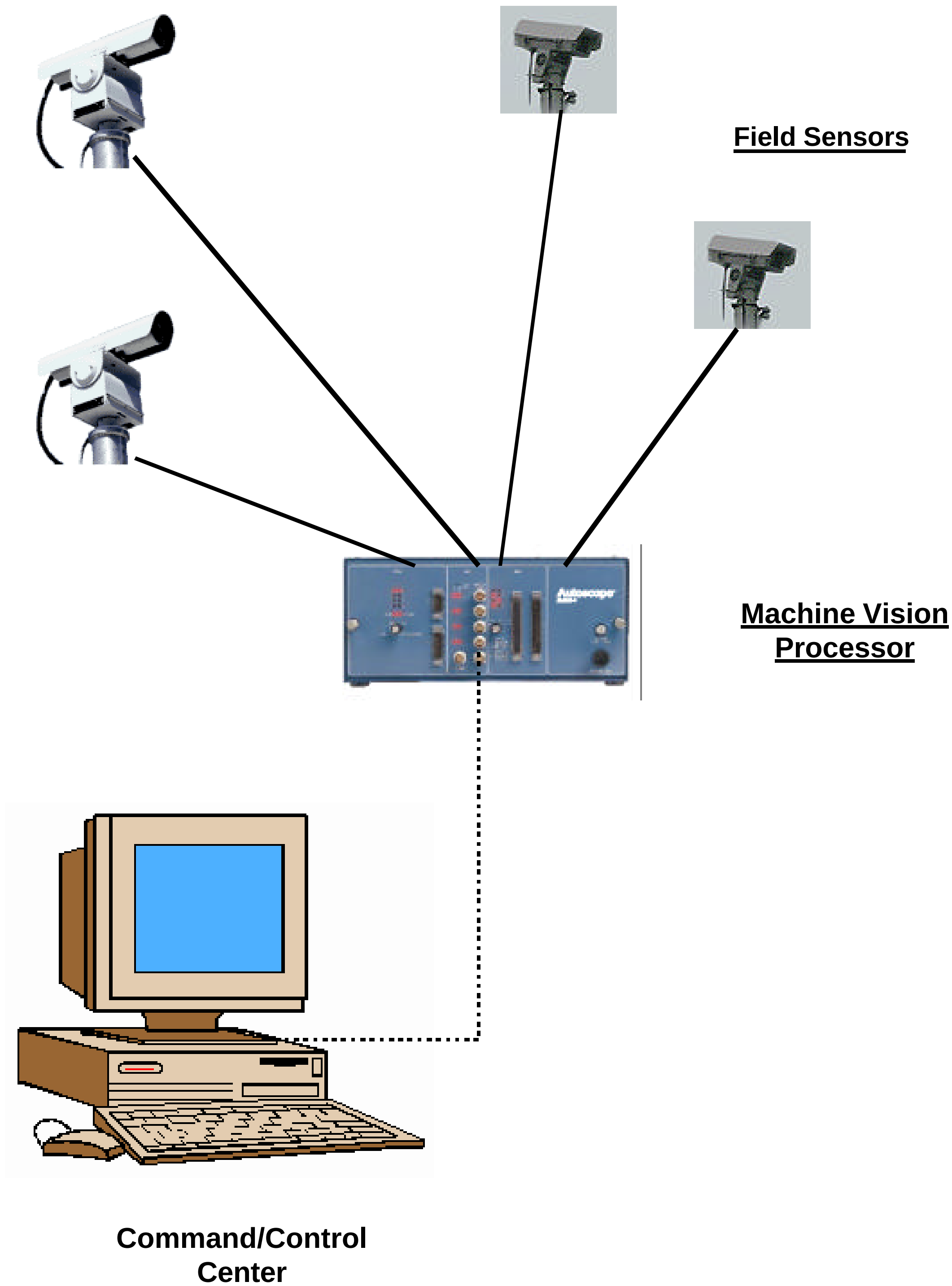

Figure 5.6-1 Video Detection System Configurations

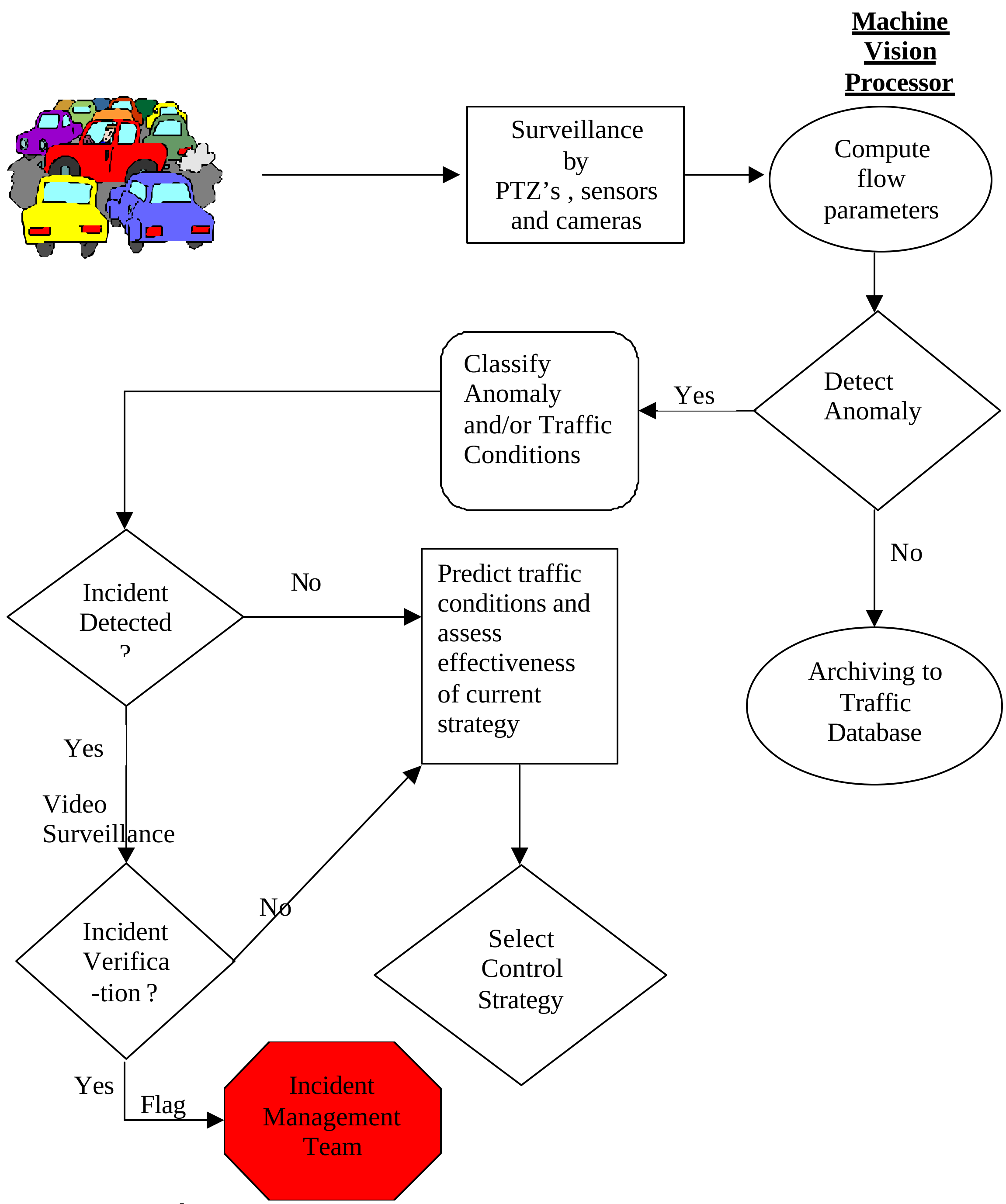

Figure 5.6-2 Machine Vision Processing Process

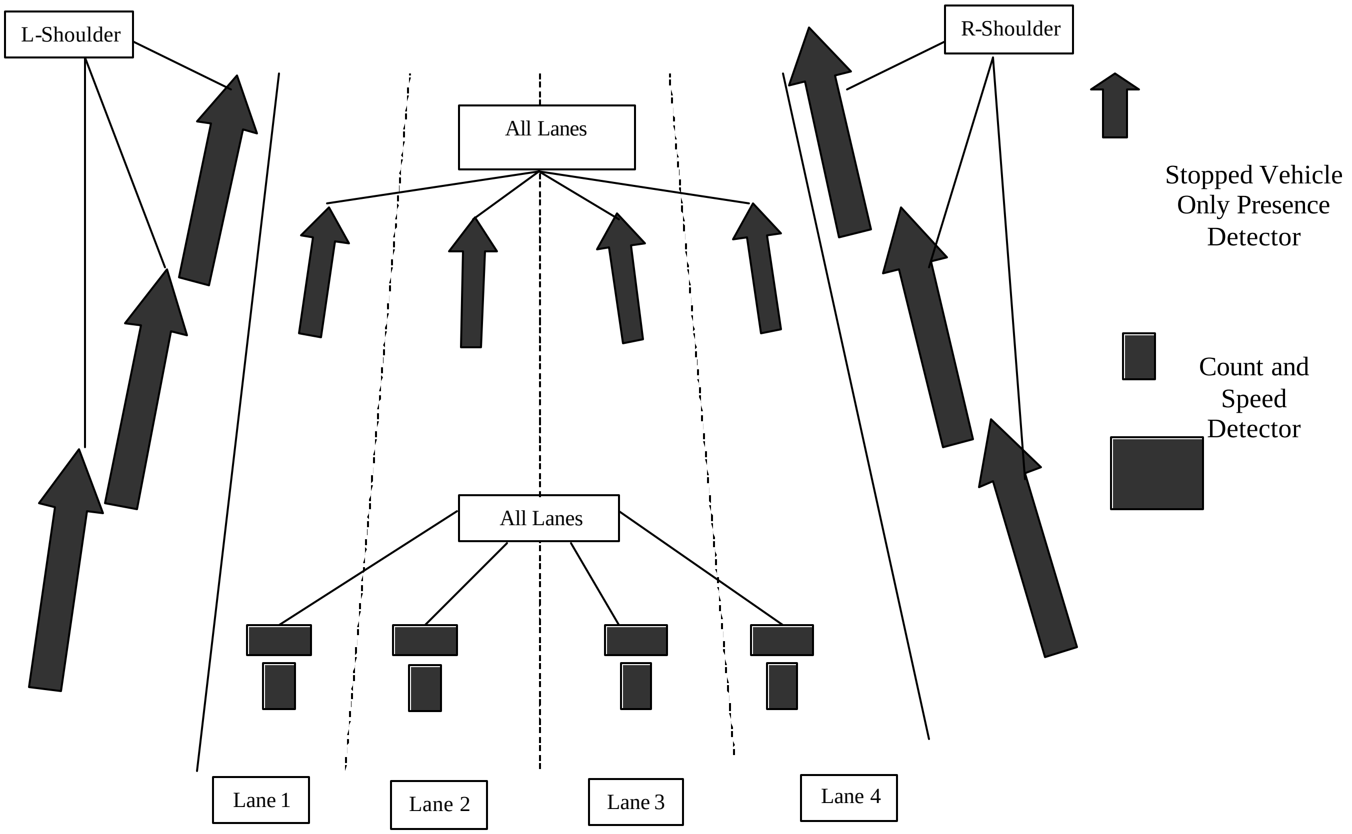

Figure 5.6-3 Virtual Detection layouts

CHAPTER 6. CONCLUSIONS

ITS technologies are deployed to address travel-related factors such as safety, mobility, efficiency, productivity, and protection of environment. They should function effectively meeting the ITS deployment requirements while addressing the dynamic variations in demand for service. Periodic and timely performance evaluations preserve the value of the systems. MOEs act as the quantitative scales for gauging the performance. This report is intended to help UDOT develop the methods for continuously monitoring the performance of ATMS and evaluate its effectiveness in real time. The cost and amount of time incurred by the current practice of field evaluations can be greatly reduced with the application of dynamic computation of MOEs. Anomalies can be identified in real time and attended, by using appropriate control strategy. Thus it can cause an overall system improvement. Not all measures are available for automation. Some methods, such as VMS or Arterial travel time evaluations, still require manual data collection. Intersection turning movements are difficult to collect automatically without using machine vision or extensive detectors being location at each intersection.

The algorithms provided for surface street, queue, ramp meter queue, freeway management including HOV lanes, should be integrated into an application that computes the MOEs depending on its the data source. Each algorithm has to be transformed into a software language for it to be implemented.

An example purpose for the continued monitoring would be on the HOV travel time savings. A travel time saving of less than five minutes when compared with the other lanes on freeways may indicate inadequate performance by the HOV lanes. Control strategies like opening of HOV lanes to general traffic during off peak hours could then be evaluated by considering the travel time saving obtained by using it during those hours. Another would be a frequent occurrence of “detector black out” situations at arterial system detectors, which would indicate long queuing, and a potential problem location that needs further study and investigation. Therefore, monitoring MOEs in real time provides valuable information in selecting and adjusting control strategies for making the ATMS more productive and effective.

CHAPTER 7. RECOMMENDATIONS AND FUTURE RESEARCH

The traffic data generated as part of the automated MOEs can be stored for future reference. Such an archived data finds use in the development of offline studies and investigations. System reliability and stability require historical data, such as travel times along a particular route over long time periods. The estimated values can be used in providing information for traveler information systems, which require reliable and timely information. The archived data can serve as a repository for studies where past performance of a system is needed, such as in cost-benefit analyses. An example of a trend showing slow speeds along a road section would indicate a poor functioning system, which can then be further evaluated to determine an appropriate strategy.

This can be further expanded to create a historical database system having query capable functionalities. To support this process, the data requires retrieval from the archival database, which can be is cumbersome if done manually. Further it would be tedious to generate charts and maps for representing a few performance measures. Mr. Martin Knopp of UDOT has developed a database with a user-friendly graphical interface that automates reproduction of charts, maps, graphs, and also compute performance measures when invoked by the user. Further examination of Mr. Knopp's system and possible additions to include other UDOT needs would provide an archival system with a more robust query capability. Including some of the various data sources and algorithms discussed by this report into this developing software will provide a more complete tool for UDOT.

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